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Tetrahedron Letters 44 (2003) 6379–6382

TETRAHEDRON LETTERS

Metal triflates–methanesulfonic acid as new catalytic systems: application to the Fries rearrangement

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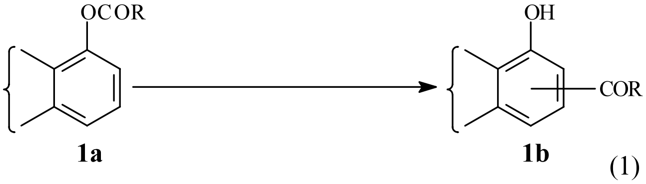
Received 20 June 2003; revised 27 June 2003; accepted 27 June 2003

Abstract—A surprising synergistic effect has been discovered between metal triflates (Mg, Ca, Sc, Cu, Zn, Y, Ln, Bi) and methanesulfonic acid, leading to active catalytic systems for the Fries rearrangement. In particular, the systems based on yttrium and copper(II) triflate proved to be very active and much cheaper than scandium triflate. The efficiency of these systems might result from the *catalytic* Lewis acid activation of Brønsted acids.

Superacidic systems which may be formed by mixing appropriate Lewis and Brønsted acids have been the subject of much academic and industrial research.[1] Trifluoromethanesulfonic acid (TfOH), which can be considered as a super-acid,[2] forms water-stable salts with non-hydrolyzable metals.[3] The use of the commercially available metal triflates such as rare-earth metal triflates (RET) as catalysts in organic synthesis has been the subject of numerous publications.[4] As triflic acid is one of the most acidic monoprotic organic acids,[1] one might hypothesize that mixing catalytic amounts of RET with any organic acid (such as carboxylic or sulfonic acids) exhibiting a much higher pK_a than TfOH would not lead to the formation of TfOH but to the complexation of the acid to the RET.[5–7] Such complexation (ideally between an inactive metal triflate and an organic acid inactive towards a specific reaction) which depends on the affinity between both partners may lead via the enhancement of the Brønsted acidity to active catalytic systems. Among all electrophilic aromatic substitutions we have studied the Fries rearrangement (FR) (Eq. (1)).[8]



1a **1b** (1)

For this reaction, classical Lewis acids (such as $AlCl_3$ or $TiCl_4$)[8] must be used in excess (1.1–3 equiv.) and therefore lead to corrosion and environmental problems due to the large amounts of acidic effluents and solid wastes. More recently, a new generation of Lewis acids such as metal triflates (scandium[9] and hafnium[10]) have been reported as catalysts. Our results using mixtures of metal triflates and organic acids as catalytic systems are summarized below.

Using the FR of naphthyl acetate (**1a**) as a model reaction (Table 1), it emerges that most of components are separately inactive (except for scandium and bismuth triflates, entries 4 and 12) or poorly active (see entry 1 where methanesulfonic (MSA) was used alone) and that powerful synergistic effects are observed when metal triflates are mixed with MSA. Moreover, it should be noted that MSA is a cheap sulfonic acid, environmentally benign, commercially available in its anhydrous form, and easy to handle.[11] It should be noted that the use of Group 2 triflates lead to active catalytic systems and that the system $Cu(OTf)_2$–MSA is also active and cheaper than scandium triflate. As the mixtures of scandium or yttrium triflates and MSA are the most efficient (Table 1, entries 4 and 7), we decided to use these catalytic systems in the rearrangement of other phenolic esters (Table 2). From these results it emerges that the combination of $Y(OTf)_3$ or $Sc(OTf)_3$ with MSA is very efficient towards the esters derived from 1-naphthol and to a lesser extent towards those derived from phenol. Conversely to the results previ-

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doi:10.1016/S0040-4039(03)01599-5

Table 1. Screening of catalysts for the Fries rearrangement of 1-naphthyl acetate (**1a**)[a]

Entry	$M(OTf)_n$	Yield in **1b** (%)[b]	
		Cat.: $M(OTf)_n$	Cat: $M(OTf)_n$+MSA[c]
1	None		4[d]
2	$Mg(OTf)_2$	0	46
3	$Ca(OTf)_2$	0	67
4	$Sc(OTf)_3$	93 (67)[f]	74[e] (82)[f]
5	$Cu(OTf)_2$	6	90 (34)[f]
6	$Zn(OTf)_2$	30	84 (26)[f]
7	$Y(OTf)_3$	0	90 (52)[f]
8	$La(OTf)_3$	0	90 (22)[f]
9	$Nd(OTf)_3$	0	90
10	$Dy(OTf)_3$	0	90
11	$Yb(OTf)_3$	2[g]	90
12	$Bi(OTf)_3$	80 (40)[f]	88 (70)[f]

[a] Reactions carried out at 100°C using toluene as the solvent (c = 0.867 M relative to **1a**).

[b] Isolated yields of 1-hydroxy-2-naphthyl methyl ketone (**1b**) after 5 h heating at 100°C (oil bath).

[c] **1a**/$M(OTf)_n$/MSA = 1/0.05/0.1 molar ratio.

[d] In this case only MSA was used.

[e] The lower yield is mainly due to side reactions of **1b** leading to not analyzed highly colored adducts.

[f] In parentheses, yield after 1 h heating (oil bath).

[g] See Ref. 10.

ously reported,[9] it should be noted that in our case, the addition of acetic acid to $Sc(OTf)_3$ did not increase the yield of **1b**. Furthermore, the combination of MSA with other salts of yttrium such as $Y(NTf_2)_3$[12] or $Y(OMs)_3$[13] did not lead to active catalytic systems. Toluene can be replaced advantageously by nitroethane (a similar yield was obtained under the same conditions as entry 11, Table 2), an industrially acceptable solvent (in contrast to nitromethane which is potentially explosive in the presence of strong acids).[14] Interestingly, the FR of naphthyl benzoate has been carried out and gave a 72% yield of 1-hydroxy-2-naphthyl phenyl ketone (Table 2, entry 10).

From a mechanistic point of view, we believe that the observed synergistic effects might proceed: (i) via a pure Brønsted catalysis (Scheme 1, path (a) since these rearrangements are known to be proton-catalyzed;[8b–d] (ii) via a ligand exchange between MSA and the metal triflate, generating metal sulfonate and TfOH which is a known catalyst for the FR[8d] or (iii) via a Brønsted Lewis acid catalysis (BLA)[15] resulting in the double-activation of the ester as previously reported in the case of the ene-reaction[6] (Scheme 1, path a+b). Further experiments[16] proved that the hypothesis of a ligand exchange could be ruled out in the case of yttrium(III) triflate and bismuth(III) triflate, this latter being previously known to be prone to give comparable ligand exchanges.[17] Moreover, intermolecular or intramolecular acylation transfer have been postulated for the FR.[18] In the case of **1a**, when toluene was substituted by anisole (same conditions as entry 7, Table 1) no *p*-methoxyacetophenone was detected, suggesting that the mechanism may involve an intramolecular transfer.

Our results suggest that the role of the metal could be displaced from a Lewis acid behavior towards the reactants to a Lewis acid behavior towards MSA, thus

Table 2. Catalysis of Fries rearrangements by MX_3–AH catalytic systems

Entry	Aromatic substrate[a]	Catalytic system		Product, yield[b] (%) and time
		MX_3	AH	
1	**1a**	$Sc(OTf)_3$	None	**1b**, 67, 1 h
2	**1a**	$Sc(OTf)_3$	CH_3CO_2H	**1b**, 55, 1 h
3	**1a**	$Sc(OTf)_3$	MSA	**1b**, 82, 1 h
4	**1a**	$Y(OTf)_3$	CH_3CO_2H	**1b**, 52, 1 h
5	**1a**	$Y(NTf_2)_3$	CH_3CO_2H	**1b**, 20, 1 h[c]
6	**1a**	$Y(OMs)_3$	CH_3CO_2H	**1b**, 3, 5 h[d]
7	**2a**	$Y(OTf)_3$	CH_3CO_2H	**2b**, 82, 5 h
8	**3a**	$Y(OTf)_3$	CH_3CO_2H	**3b**, 87, 5 h
9	**4a**	$Y(OTf)_3$	CH_3CO_2H	**4b**, 80, 5 h
10	**5a**	$Sc(OTf)_3$	CH_3CO_2H	**5b**, 72, 16 h[e]
11	**6a**	$Y(OTf)_3$	CH_3CO_2H	**6b**, 60, 2 h 30[f,g]
12	**7a**	$Y(OTf)_3$	CH_3CO_2H	**7b**, 60, 2 h 30

[a] Conditions: Aromatic substrate/MX_3/AH = 1/0.05/0.1 molar ratio except for entry 10 where this ratio is 1/0.1/0.2 and entries 11 and 12 where this ratio is 1/0.2/0.4. Reactions carried out at 100°C using toluene as the solvent (c = 0.867 M relative to the aromatic substrate) except for entries; aromatic substrates: naphthyl acetate (**1a**), naphthyl hexanoate (**2a**), naphthyl isobutyrate (**3a**), naphthyl cyclohexylcarboxylate (**4a**), naphthyl benzoate (**5a**), 3-methoxy-1-phenyl acetate (**6a**), 3-methyl-1-phenyl acetate (**7a**).

[b] Products: 1-hydroxy-2-naphthyl pentyl ketone (**2b**), 1-hydroxy-2-naphthyl isopropyl ketone (**3b**), 1-hydroxy-2-naphthyl cyclohexyl ketone (**4b**), 1-hydroxy-2-naphthyl phenyl ketone (**5b**), 2-hydroxy-4-methoxyphenyl methyl ketone (**6b**), 2-hydroxy-4-methylphenyl methyl ketone (**7b**).

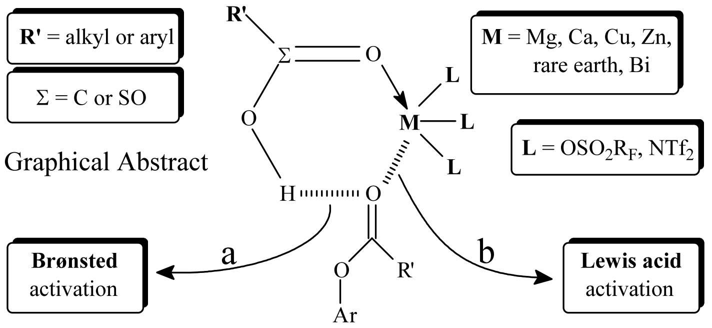
[c] Only traces of **1b** were obtained under the same conditions when $Y(NTf_2)_3$ was used alone.

[d] No reaction occurred under the same conditions when $Y(OMs)_3$ was used alone.

[e] This experiment has been carried out at 150°C using 4-chlorotoluene instead of toluene.

[f] This experiment has been carried out in nitroethane instead of toluene and gave a similar yield.

[g] Containing 4-hydroxy-2-methoxyphenyl methyl ketone (yield 7%).



Scheme 1.

forming the active catalytic system. In this view, the metal triflate could be described as a procatalyst for the reaction considered, the other partner of the catalytic system being voluntarily added (this work) or in situ generated during the reaction. Effectively, $Sc(OTf)_3$ has been reported as a catalyst for the alkylation of aromatics with alkyl methanesulfonates leading to alkyl aromatics and MSA.[19] Based on our findings it seems attractive to consider that the real catalyst might be $Sc(OTf)_3$-MSA and not $Sc(OTf)_3$.

Typical procedure for the rearrangement of naphthyl acetate (**1a**). In a 50 mL Schlenk tube were introduced under argon 70 mg (130 μmol) of yttrium triflate and 483 mg (2.6 mmol) of **1a**. 3 mL of toluene was introduced and finally 25 mg (260 μmol) of MSA was added via a syringe. The suspension was magnetically stirred and heated in a thermostated oil bath at 100°C for 5 h. After this time, the red solution was cooled, 50 mL of a saturated aqueous solution of sodium bicarbonate were added and the organic products were extracted with dichloromethane (2×50 mL). The combined organic phases were dried over sodium sulfate and concentrated under reduced pressure. The product was purified by flash chromatography (silica gel, eluent: pentane/dichloromethane = 1/1) to give 435 mg (90% yield) of 1-hydroxy-2-naphthyl methyl ketone (**1b**), identified with an authentic sample.[9]

In conclusion, we have demonstrated that mixing metal triflates with methanesulfonic acid leads to an extremely synergistic effect, thus generating a new set of active catalysts for the Fries rearrangement. Due to their highly tunable potentialities (by reason of the choice of the appropriate R′, Σ, M, L), we believe that this new family of catalytic systems might enrich the already wide field of catalytic applications of metal triflates towards organic synthesis. The extension of this work to other reactions is currently under investigation in our laboratory.

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